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Soil Constitutive Behavior Under Different Environmentally Friendly Cementitious Materials

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Abstract

Gypsum soils are problematic soils which are prone to a sudden and large volume changes (collapse) upon reduction in suction stress (wetting). Fly ash is a by-product material of coal combustion which is produced in huge amounts around the world and thus causes environmental pollution. Fly ash is a chemical stabilizer used to strengthening these soils under pozzolanic-chemical reactions and especially used highways roads construction. To examine the change in porosity, void ratio, and the collapse potential (CP) during the change in the physical and chemical properties of pore water in the soil, there are many tests, among which the electromagnetic properties test was used. The present paper is aimed to study the change of electromagnetic properties during the suction stress reduction on (CP) of fly ash stabilization soil. Four compacted soils with various cementation materials (fly ash and gypsum martial) were used. All samples were in dry and nearly complete saturation by coaxial line cells prior to the assay as

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samples were tested at frequencies ranging from 1 MHz to 10 GHz for all samples. The results show there is strong link between the electromagnetic measurement and the (CP) of soil during the suction change. The soil mixed with gypsum show the lower in permittivity value and the highest (CP). It was found that when adding stable fly ash, the soil structure was provided with a reinforcing bond, thus reducing the (CP) as well as increasing the permittivity value.

Keywords: Artificial Gypsum soils, fly ash stabilization, thermo-hydro mechanical, sustainability

1 Introduction

Several engineering problems are associated with compacted fills in an unsaturated state which used as a foundation in structures such as road sub-grades, earth dams and embankments in both arid and semi-arid regions, with unstable water level in soil where it is moving up and down during the change climate state. Collapsible soils is one of the problematic soils which classified to several types: as a loose soil material (high void ratio) with a low water content in the field condition, compacted collapse martials with high changed in physical-chemical properties during increasing in water content and collapsible gypsum soils which content high gypsum material. Upon wetting proses a large and sudden volume changes (collapse) will occur [1].

The difference between the water-air pore pressure interaction in unsaturated state of these soils cause inter-particle stress resulting to the capillary tension force “suction” between the particles and the water molecules which it gives enough strength to connect the particles a mongo them. With an increase and decrease in the water content of the soil, which is associated with an increase and decrease in the soil absorption capacity, the mechanical behavior of unsaturated collapsible soils is signification changing such as increasing in volume change, increase in (CP) [2].

The (CP) is influenced mainly by the chemical-physical behavior of the clay sheets and as described in the double layer theory. Given that the double layer forms around the clay plate, which is characterized by its small size and spread around the slab, the forces of the clay plate are mainly controlled by the chemical forces that bond to this double layer. In the dry state, the porous water contains a high concentration of ions. Therefore, the bonding forces between the clay plates, the "attraction force", are rather high. In addition, when drought, the thickness of the double layer is less, which leads to the affinity of particles and thus increased tissue strength. Conversely, when saturated, the pore water contains a low concentration of ions due to the high water content. As a result, the size of the double layer will significantly increase and the "repulsion force" will increase, so the clay particles will disperse, leading to weak tissue strength and soil breakdown. [3].

Soil can be considered as gypsum soil when it contains hydrated calcium sulphate($CaSO4$), which called gypsum at a rate of more than 2%, and it is one of the types of soils that are subjected to collapse. The primary function of gypsum in soil is to act as a bonding material between soil particles, making it very hard when the soil is dry. When moistened, the gypsum will dissolve and thus the soil will lose the bonding material between its particles, making it compressible and soft, and thus lead to additional problems, especially in foundation work due to soil collapse. The study of the properties of gypsum soils using samples taken from the fields is considered a difficult study due to the possibility of the formation of an open and stable tissue during sampling. In addition, obtaining natural undisturbed samples from gypsum soils sites is very expensive [4]. To avoid these difficulties, artificially gypsum soils have been used in this paper to study their collapsibility properties.

In this case, soil stabilizers are used in order to maintain its strength and prevent collapse when exposed to loads. In this research, the use of fly ash as a soil stabilizer was studied, where it is applied as a binder to increase soil strength. Fly ash can be a good alternative to traditional fasteners that are relatively expensive and unavailable in some areas. On the contrary, the use of fly ash has high economic benefits as it is a by-product of coal combustion and thus causes environmental pollution. The use of fly ash in the soil reduces the need to produce other stabilizers and thus reduces the costs of greenhouse gas emissions. When fly ash is added to water-containing soil, many reactions will occur as a result. Consequently, the lime present in the binders will disintegrate and form cementitious and pozzolanic materials, thus the hardness and shear strength will increase, as well as decrease in the possibility of collapse. [5].

The electromagnetic test of the pore fluid is used for the purpose of estimating the physicochemical properties of the soil that directly affect the strength of the clay plates. This electromagnetic test is influenced by many factors including pH, ionic concentration, permittivity of the spaces, and valence. [6, 7]. Yet, there is no study was carried out to assess the use of electromagnetic test to monitor the soil-fly ash reaction. The ability to detect the change in fabric of stabilized-soil during the change suction by using theses technique would be more beneficial to engineering applications.

This research aims to study the electromagnetic properties of fly ash used to stabilize industrial collapsible gypsum soils during suction variation in addition to investigating the (CP) for the same soils.

2. Materials &Methodology

2.1 Materials

In this research, samples of unstable and collapsible soils were studied. From studying the characteristics of the samples, it was found that their water content and dry unit mass were relatively low.. Table (1) shows the mineral and physical properties of the samples used.

Fly ash was obtained for this study from an electric power production plant located in the east of Essen, Germany, and the ash was of (Steament H-4) type. The chemical analysis of the Steament H-4 revealed that it mainly composed of (SiO_2= 53.6, Al_2O_3=24.9, Fe_2O_3=7.6 and CaO =2.9) and in comparison with the typical amount of the fly ash chemical composition, it is close from class F [8].

Table 1: Physical and Mineral properties of soil used

Physical properties	Values	Mineral analysis	% by weight
Specific gravity [g/cm^3]	2.7-2.72	Mica	25
Initial water content w_c [%]	5-10	Smectite	7
Liquid limit (%)	36.3		
Plastic limit (%)	17.8	Kaoline	3
Plastic Index (%)	18.5	Chlorite	5
Clay content %	34 – 33	Tecosilicates	44
Silt content %	42 – 41	Carbonates	12
Sand content %	21 – 20	Gypsum	1
Gravel content %	3 – 6	Goethit	2
Classification according to (ASTM D248)	Sandy clay	Organic	1
Property		Value	
pH		8.8	
Electrical Conductivity		628 µs/cm	
surface area (m^2/g)		22.95	
Sulphate mass rate %		0.88	
Sodium Adsorption %		7 – 16	
Sodium Exchange Rate %		9 – 19	

2.2 Samples Preparation

Four types of soils were mixed with various cementation materials. To achieve complete homogeneity and curing, the mixed samples were kept in closed boxes for a week. Samples were categorized as two types:

1. Suction – Controlled Test Samples (Oedometer Test)

This test was conducted to determine the (CP) during the change of soil suction. From each box of soils mixed, several samples with (50mm diameter and 20mm height) were prepared.

2. Electromagnetic test Samples

In order to conduct the electromagnetic properties test, the characteristics of the samples are recorded initially and then they sampled as cylinders (10 mm in diameter and 15 mm in height).. After that, small samples were prepared for the purpose of testing the electromagnetic properties, with samples with an external diameter of 38.8 mm and 15 mm of an inner diameter and a height of 50 mm.. These samples were used to conduct an examination of the electromagnetic properties of two conditions of saturation: a state of dryness with air and a state of near saturation, where they were saturated with water using ceramic stones for 7 days.. Table (2) illustrates the properties of initial condition, after near saturated of electromagnetic samples

Table 2: The properties of initial condition and after near saturated of electromagnetic samples used

Properties	Case	Wc [%]	θ [%]	ρ_d [g/cm^3]	n [%]	e [-]
Soil (S)	Air-dry	4.6	8.1	1.747	34.8	0.534
	Saturated	20.7	33.3	1.61	39.9	0.665
Soil +15% fly ash (SFA)	Air-dry	11.2	17.8	1.591	40	0.682
	Saturated	23.1	36.6	1.585	40.2	0.698
Soil +30 % gypsum (SG)	Air-dry	5.9	9.2	1.556	40.6	0.664
	Saturated	21.4	33.9	1.579	39.7	0.672
Soil+30 % gypsum+15 % fly ash (SGFA)	Air-dry	9.2	13.9	1.515	41.1	0.658
	Saturated	25.3	37.7	1.492	42.1	0.725

2.3 Suction Control-Collapse Test

This test was done by special suction control-collapse cell named "UPC-Barcelona cell" (see for details [9]). The maximum value of vertical load that was performed was 400 kPa and the minimum was 50 kPa with a mean value of 200 kPa.. The samples were first vertical loaded and impinged with a high initial suction. After achieving equilibrium, the suction force was gradually reduced until reaching zero, with a gradual addition of water in the form of multiple steps. During these steps, the corresponding deformations were recorded, in addition to the water content, CP, void ratio and porosity.

2.4 Electromagnetic technique

Collapsible soils that are unsaturated are mainly composed of four components with different physical states: solid particles that include different mineral phases, pore fluid, pore air, and the interface between solid particles and pore liquid.. Since the factors of composition, surface area and specific density differ from one place to another, the parts of the four mentioned stages differ according to the place. In addition, they differ according to time as the factors of moisture content, temperature, porosity and water chemistry are considered as time related [10]. As a result, the collapsible soil used is considered to be an electrical, strong, insulating, and dispersive material, with its electromagnetic properties are to be frequency dependent..

The functions of broadband electromagnetic transmission as complex effective electrical conductivity and complex effective relative permittivity (CERP) $\varepsilon^{*}{}_{r,eff}$ are considered for the purpose of defining electromagnetic properties with $j = \sqrt{-1}$, angular frequency $\omega = 2\pi f$ and permittivity of free space ε_0 [7, 10]. Rohde & Schwarz ZVR with frequency capacity range (1MHz – 4GHz) to carry out the broadband electromagnetic measurements for the frequencies less than 4GHz and Agilent PNA E8363B with frequency capacity ranging between (10 MHz – 16 GHz) vector network analyser in combination with coaxial transmission line cells for studying the higher frequencies were the tests carried out for frequencies between (1MHz – 10GHz) (for details see [10, 11]).

The electromagnetic properties of the soils were characterized with a broadband generalized dielectric response (GDR) based on a superposition of three relaxation processes with considering a contribution of direct electrical conductivity (see [10, 11] for details)

3 Results and Discussion

3.1 Collapse-Suction Control Properties

3.1.1 Collapse Behavior in Natural and Gypsum Soil

As shown in figure 1, for all soils mixed, the void ratio decreased and collapse increased during the suction decreasing. It can be observed that in natural soil (S), the sample with 50 kPa vertical stresses gives an almost negligible collapse potential. The largest collapse potential value (9.5%) occurs and the void ratio reduced from 0.83 to 0.61 while suction was gradually decreased from the initial value to 0 kPa at 200 kPa vertical stress, Thus, the soil is able to compensate the decrease of suction as a type of cohesion till a certain threshold. After wards the collapse begins to become more progressive. This is resulted from many reasons, including the dissolution of the clay bridge, the alteration of chemical bonds, as well as the loose void ratio [12]. When the resistance decreased to below constrain of cutting levels, the resistance of clay bridges between grains collapses during wetting [13] and [14] suggested that collapses occurrence was attributed to the capillary suction decrease in soils.

The change of chemical bonding effect is due to physical-chemical reaction of the ion exchanging. When high primary suction is applied with low moisture content, the menisci will attract fine particles, so the pore fluid will contain higher ionic concentrations. According to the effect of the van der Waals attraction, which dominates the repulsion force between the two layers, the thickness of the two layers will shrink as well as salt bridges are formed which contribute to the acceleration of tissue strengthening. On the contrary, when moistening, most of the aforementioned processes that work to strengthen the tissue will behave in the opposite way, where the ionic concentration in the liquid decreases with the increase in the water content in addition to the dissolution of the salt bonds and the thickness of the double layers increases significantly. As a result, the formations of clay will decrease resulting in larger hydration layers. At this stage, the effect of the forces of attraction decreases, the force of repulsion between the layers increases and the clay particles are dispersed, which leads to collapse even before reaching complete saturation in some cases because the tissue needs simple effective loads in addition to its own weight to collapse [8].

In gypsum soil (figure 1(bottom)), it can be seen a clear high drop in void ratio value in addition to high collapse value after the suction was reduced to 300 kPa. The soil mixed with gypsum material (SG) gave a lower strength, the highest value in collapse potential (Cp=13.2%) and reduction in void ratio value from 0.83 to 0.54 at 200 kPa vertical stress stress during increase in water content when it compared with others soils and. This is duo to gypsum material affect which it has a low density, low specific gravity. Gypsum acts as a binder, especially in dry conditions, which gives the soil a high hardness compared to the wet state. In the wet state, the soil is compressible and soft, and this can be attributed to the dissolution of part of the binder when the water content increases, and thus the soil loses the bonding material and causes lower resistance and then may collapse [12].

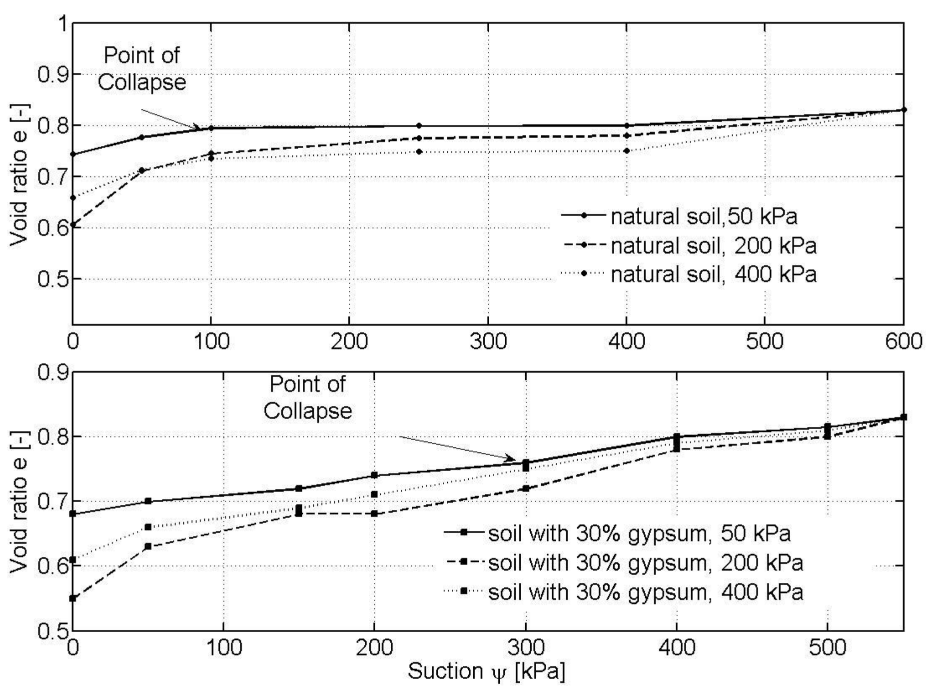

Fig. 1*:* relationship between void ratio and soil suction with different vertical stresses (top) for normal soil (bottom) for soil with 30% gypsum

3.1.2 Fly Ash Effect on Collapse Behavior

The results revealed that adding fly ash for two soil types (S and SG) had increased both the resistance and the soil strength with lower voids ratio and collapse potential. The largest decrease in the void ratio was at a pressure of 200 kPa, as the void ratio decreased from 0.83 to 0.7. Moreover, when adding 15% fly ash, the collapse potential was decreased from 9.2% to 4% for soil (S) and from 13.2% to 7.5% for SG soil This can be attributed to the reactions that occur to the lime when the ash is mixed with the soil with the high water content. These reactions lead to the dissolution of the lime in the binder material leading to the formation of cementitious and pozzolanic gels, including calcium silicate hydrate (symbolized by (CSH)) and calcium aluminate silicate hydrate(symbolized by (CASH)). These reactions are called as pozzolanic and cementitious reactions, which produce cementitious and pozzolanic gels.. The results revealed a slight correlation for both the decrease in the value of soil collapse and the increase in strength in normal soils with the results obtained from the interactions if the CSH was to obtain a pozzolanic gel and a short-term strength, as for CASH to obtain a long-term strength.. The generation of these pozzolanic materials leads to their penetration into the gaps, which leads to fewer gaps, and thus the soil compound will have a higher density. [5].

A scanning electron microscopy (SEM) was conducted to the soil with 15% fly ash, and the results showed that the chemical reactions that took place led to an increase in stiffness and strength. Figure 3 shows the (SEM) image. The primary function of the binder is to enhance the solid soil material and thus increase the soil hardness.

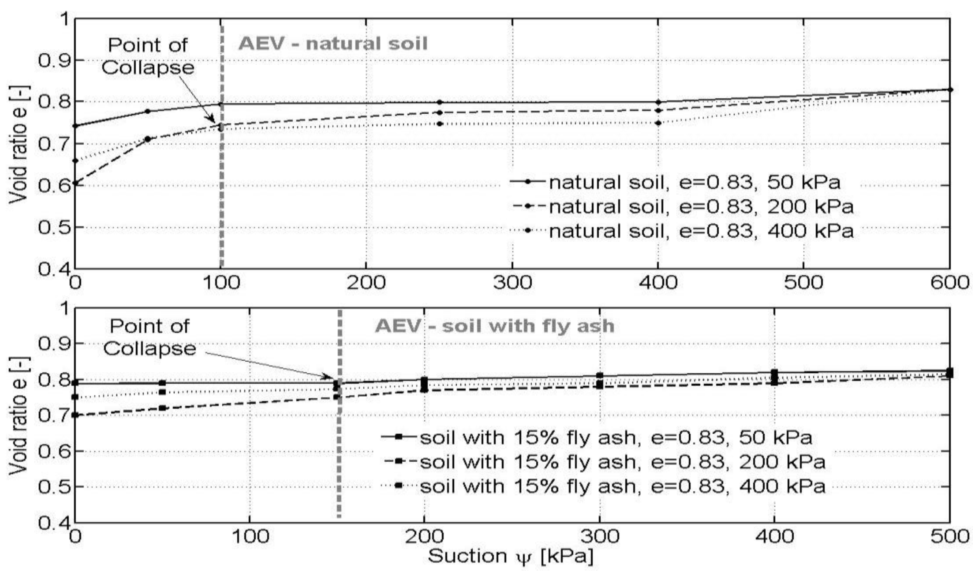

Fig. 2: relationship between void ratio and soil suction with different vertical stresses (top) natural soil (bottom) soil mixed with 15% fly ash

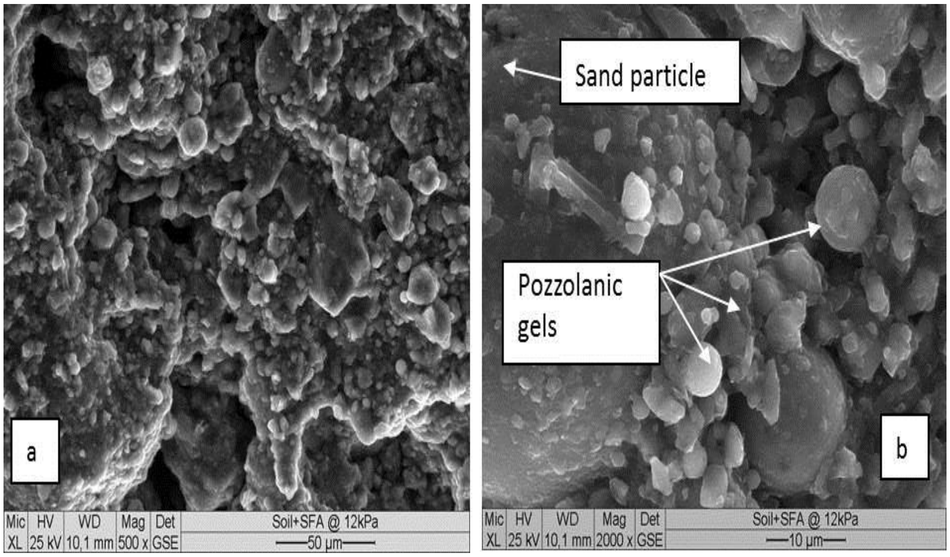

Fig. 3: SEM image for soil with 15% fly [a] 50µm diameter and [b] 10 µm diameter

3.2 Electromagnetic Material Properties

Figure 4 shows the values obtained from examining the electromagnetic properties represented by the moisture content and the effective relative permittivity that give a measure of the porosity.

In the range of tested frequencies, all examined samples showed clear dispersion and high absorbance. Nevertheless, dispersion was low with high frequencies (above 1 GHz) and low frequencies (less than 10 MHz).. In addition, as shown in Table 1, it has been observed from broadband parameterization results that the high frequencies contributed significantly to water relaxation.. As a result, in high frequencies when comparing between $\varepsilon'_{r,eff}$for the tested moister contents imply that the volumetric moisture content dominates the dielectric soil properties.

On the contrary, σ'_{eff} is strongly affected by the occurring relaxation processes due to the direct relationship with the imaginary part of the complex effective permittivity. Therefore, σ'_{eff} denotes the differences in the mineralogical as well as chemical soil properties which suggest using σ'_{eff} as proxy for the soil type. Therefore, the entire spectral information of the soil electromagnetic properties contains valuable information as a starting point to develop tools for the classification of soils and therefore the prediction of important soil physical properties such as the collapse behavior [12].

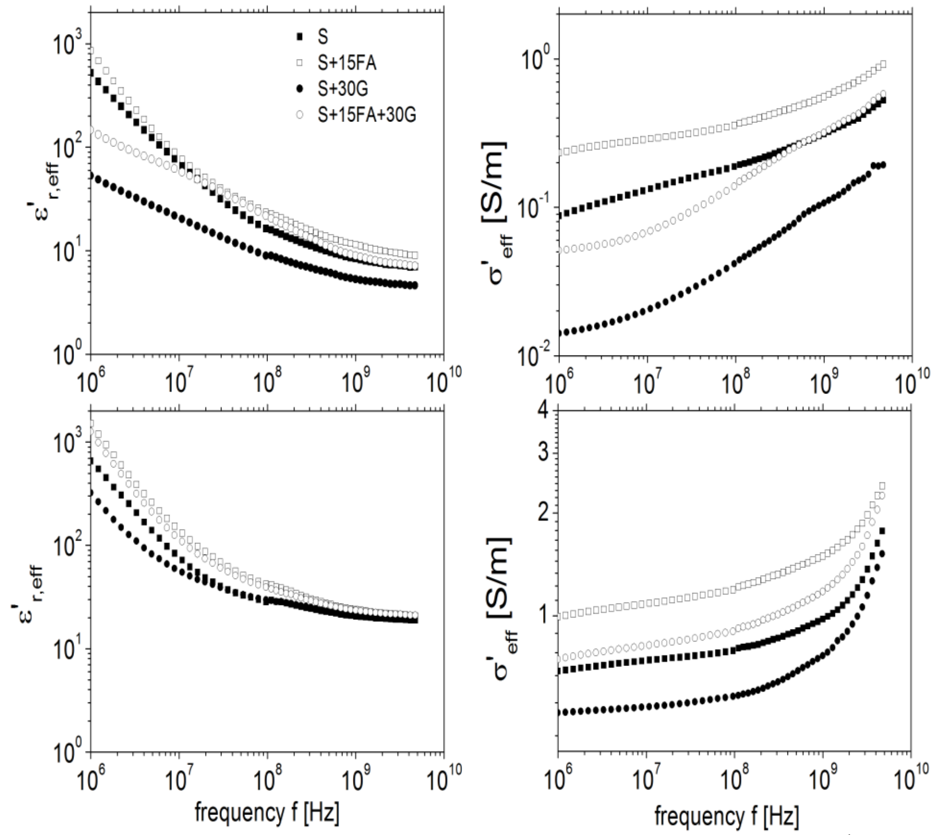

Fig. 4: (left) Real part $\varepsilon'_{r,eff}$ of the CERP $\varepsilon^*_{r,eff}$ and (right) real part σ'_{eff} of the complex effective conductivity of the investigated soils(top) at natural water content and (bottom) at saturation.

Table 3: Relaxation parameters of the different soils at two states [8].

Properties	*units*	*S*	*S15F*	*S30G*	*S15F30G*	*S*	*S15F*	*S30G*	S15F30G
		Air-dry case				*Saturated case*			
$\varepsilon'_{r,eff}$ at1 GHz	[-]	8,4	11,5	5,3	8,9	20,7	24,0	21,3	23,6
σ'_{eff} at 1 GHz	[S/m]	0,310	0,557	0,107	0,314	0,980	1,450	0,763	1,180
σ	[mS/cm]	0,611	1,060	0,110	0,388	6,190	9,070	4,480	4,880

In Fig.5, a volumetric moisture content and voids ratio functions are represented by the effective real part of complex permittivity at a frequency of 1 GHz. The effective complex permittivity was modelled based on a theoretical mixture equation (see [11] for details):

$$\varepsilon^{*a}_{r,eff} = \theta \varepsilon^{*a}_{W} + (1-n)\varepsilon^{a}_{G} + (n-\theta) \quad (1)$$

Where:

- ε_G: is the solid grain permittivity which can be obtained based on the empirical equations by [15], [16] and [17].
- ε_w^* describes the well-known complex permittivity of water,
- n : porosity
- Θ : volumetric moisture content.
- The value of 'a' is represented in terms of temperature independent constants and has been selected to fit the properties of the selected collapsible soil.

The comparison between modelled and measured actual part of the effective permittivity in the elevated levels of frequencies (≥ 1 GHz) clearly indicates that the porous media effective electromagnetic properties such as soils are significantly effected by the volume fractions of the appropriate phase regardless chemical effects. This is of great value for practical remote sensing applications.

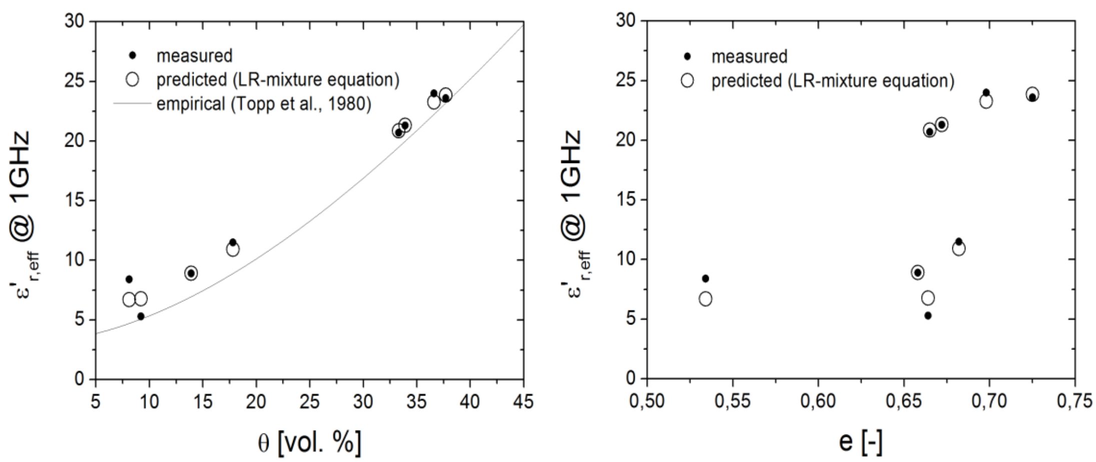

Fig. 5: Measured and calculated rearl part $\varepsilon'_{r,eff}$ of the CERP $\varepsilon^*_{r,eff}$ at a frequency of 1GHz (left) as a columetric moisture content function and (right)as a void ratio function of the investigated soils.

3.3 Permittivity – Collapse Behaviour

Permittivity is expressed as a complex number consisting of two parts (real and imaginary). For the purpose of carrying out practical applications such as (TDR, GDR… .etc.), The techniques used to determine soil properties using electromagnetic testing all use the true value of permittivity and accordingly, the real value of CERP at a frequency of 1 GHz was used to compare the collapse and permittivity values in all types of soil examined. [11].

The experiment outcomes revealed that there is a link between the permittivity and collapse value. The electromagnetic properties relationship with the collapse behaviour was carried out according to equation (1)..

Based on the suggestions by [11] at low moisture content levels, a=1/3 was used with Looyenga-Landau-Lifschitz model (LLLM), while with higher saturation (nearly saturated level), a =2/3 was used with the advanced Lichtenecker-Rother model (ALRM).

Oedometer suction control test was carried out to estimate the porosity, volumetric moisture content, and collapse value. In addition, the CERP values for all used soils with 1GHz was obtained from the electromagnetic test and equation (1) was used to implement their values.

Fig.6, show the relationship between the collapse values and permittivity during the increasing in the water content of soils used. It can be seen a clear difference behavior in real part of the CERP ($\varepsilon_{r,eff}$) for all mixed soils with various in cementation material. The rate increasing of the permittivity with the increasing in collapse potential in the gypsum soil is the highest with comparison with the other soils. This is due to the fact that the permittivity of soil a according to equation (1) is highly influenced by voids ratio and the porosity , where the variation in void ratio of gypsum soil was the highest (high collapse value). When a full saturation (Sr = 100%) reached, it was found that permittivity of all soil types remained constant after without changing in collapse potential and the permittivity at full saturated in loose soil was more than when comparison in dense soil.

The results indicated that both resistance and strength of soil to collapse were increased when adding fly ash for the two soil types used (SG) and (S). The collapse value decreased from (9.2% to 4%) and (13.2% to 7.5%) of soils (S) and (SG), respectively. This can be attributed to the reactions that occur to the lime when the ash is mixed with the soil with the high water content. These reactions lead to the dissolution of the lime in the binder material leading to the formation of cementitious and pozzolanic gels, including calcium silicate hydrate (symbolized by (CSH)) and calcium aluminate silicate hydrate(symbolized by (CASH)). The results revealed a slight correlation for both the decrease in the value of soil collapse and the increase in strength in normal soils with the results obtained from the interactions if the CSH was to obtain a pozzolanic gel and a short-term strength, as for CASH to obtain a long-term strength. [5].

The increasing in the permittivity was observed in both soils (S) and (SG) when they mixed with fly ash which is attributed to the fact that Ca^{++} and pH level of pore water were increased when the fly ash hydrated with the water presence[18]. In addition, the formation of calcium silicate hydrate started and with ion exchange between clay and the calcium ions produced from hydration of fly ash, the normal clay was converted to calcium clay. the attraction force between the double layer was increased as a result of higher Ca++ ions and consequently, the soil particles flocculated.. The new pozzolanic products blocked the voids which results decreasing in porosity and an increase in permittivity [19].

The pervious studied noted that a new empirical equation between the collapse potential/ initial void ratio and permittivity [12] and it can used this a new model to compared the collapse behavior and permittivity for all soils used as shown in figure 7.

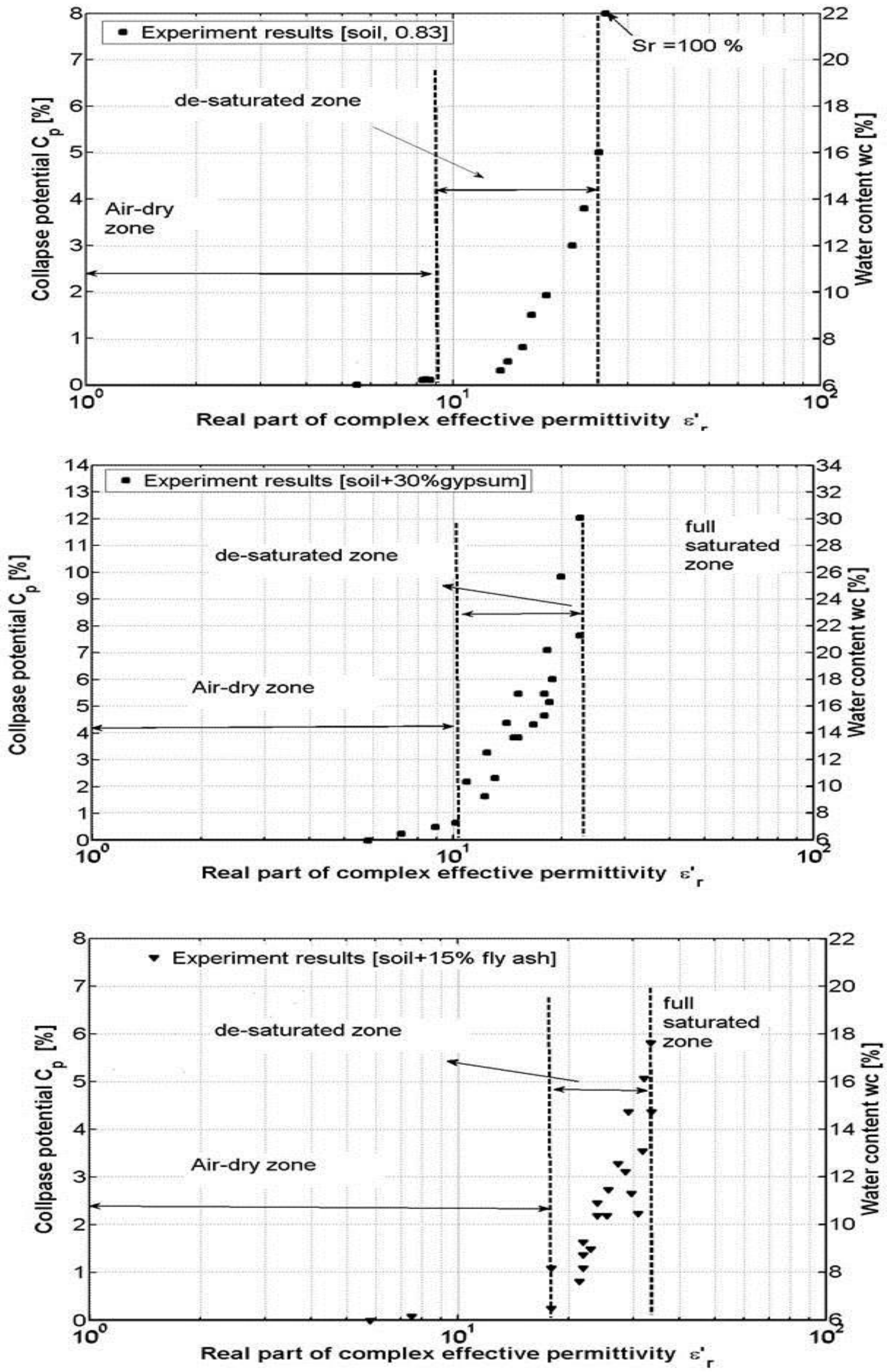

Fig. 6: Real part $\varepsilon'_{r,eff}$ of the CERP and collapse potential of soils used (from top to bottom) Soil, soil+30% gypsum and soil+15% fly ash.

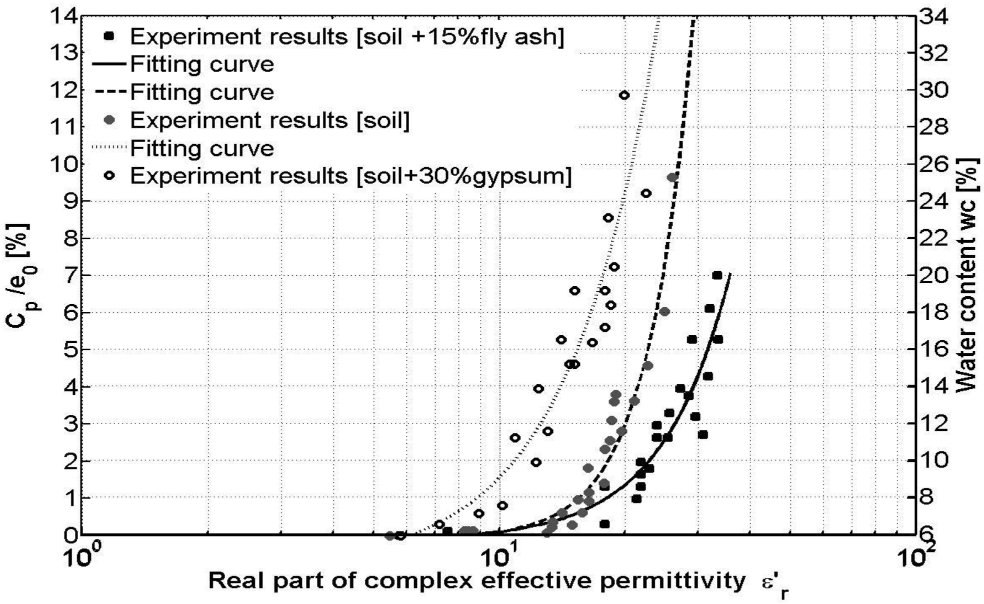

Fig.7: A relationship between collapse potential, initial void ratio and real part of the CERP of soils used

4 Conclusion

The gypsum soil is found to be a sensitive for degree of saturation variation due to the cementitious gypsum particles capability to be dissolved which leads to soil particles rearrangement and consequently the voids ratio will be changed which causes soil collapse under vertical loading. To observe the gypsum soil properties and soil treated with fly ash, the permittivity property was found an efficient investigator. The behavior of collapse – conductivity curve revealed a different attitude for the tested soils which is attributed to the variation of cementitious materials contained. Finally, the electromagnetic test was successfully used to observe the changes in fabric of soil while the cementitious materials are changing which are highly linked to the collapse potential.

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